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A deviation in internal pair conversion

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Abstract

The E1 e^+e^- decay of the 17.2 MeV level in ^{12}C , and the M1 e^+e^- decay of the 17.6 MeV level in ^8Be have been studied in a search for possible signals of short-lived neutral bosons with masses between 5 and 15 MeV/ c^2 . Whereas for the E1 decay at large correlation angles no deviation is found from internal pair conversion (IPC), surprisingly the M1 angular correlation deviates from IPC at the 4.5σ level.

A variety of experimental studies in the past has provided severe constraints on the possible existence of light neutral bosons [1–4]. Interestingly, beam dump experiment [5–7] specifically searching for short-lived neutral bosons still allow a mass-lifetime window for masses between 5 and 100 MeV/ c^2 and lifetimes shorter than 10^{-13} s. The possibility [8] to narrow this window on the low mass side motivated us to investigate suitable electromagnetic transitions for short-lived neutral bosons decaying into e^+e^- pairs with invariant mass between 5 and 15 MeV/ c^2 . Scalar (0^+) and vector (1^-) bosons may compete in electric transitions and pseudoscalar (0^-) and axial-vector (1^+) bosons in magnetic transitions.

Two-lepton decay of a boson emitted in a nuclear transition would produce a structure on top of the e^+e^- angular correlation from internal pair conversion (IPC) [9,10] and external pair conversion (EPC) [11–13]. These processes are peaked at 0° and decline for low Z nuclei rapidly with increasing ω , EPC even more drastically than IPC.

We performed an exploratory measurement on the IPC of the nuclear E1 decay of the 17.2 MeV ($I^\pi = 1^-, T = 1$) level in ^{12}C and similarly on the M1 decay of the 17.6 MeV ($I^\pi = 1^+, T = 1$) level in ^8Be . The aim was a sensitive comparison of the e^+e^- angular correlations, mutually and with standard theoretical predictions.

For this purpose a multi-detector set-up was constructed. The experiment was performed with the proton beam of the Van de Graaff accelerator at the In-

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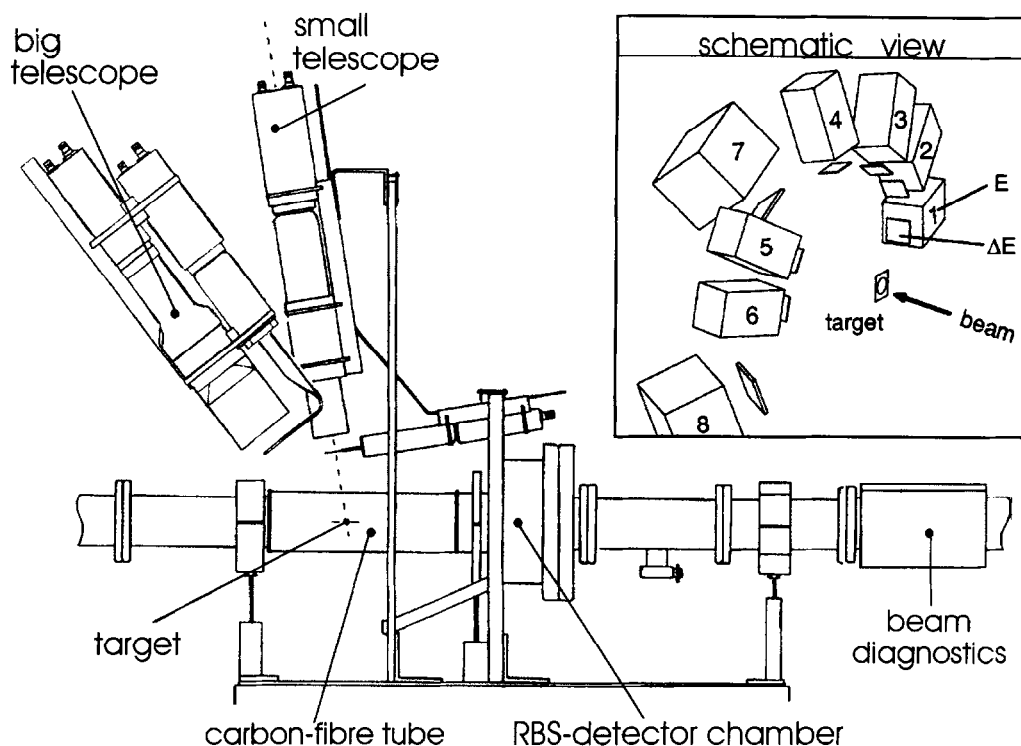


Fig. 1. Side view of the experimental set-up consisting of six small and two large ΔE - E detector telescopes, the beam tube, a Rutherford backscattering (RBS) device to monitor the target condition and a carbon-fibre tube as target chamber. For clarity only one of each sort of telescopes is depicted. In the inset the arrangement of detectors around the target is displayed in perspective. All E -detectors are 7 cm thick. The relevant dimensions for the small ΔE -detectors are: $0.1 \times 2.2 \times 2.2 \text{ cm}^3$, and for the large ones: $0.3 \times 3.8 \times 4.0 \text{ cm}^3$. The distance from the ΔE -detector to the target is around 11 and 14 cm for the small and large detectors, respectively.

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The ^{12}C resonance at 17.2 MeV with a width $\Gamma = 1.15 \text{ MeV}$ is populated in the $^{11}\text{B}(p, \gamma)^{12}\text{C}$ reaction [14,15] at 1.6 MeV bombarding energy. It decays by isovector E1 transitions to the ground state and first excited state with energies of 17.2 and 12.8 MeV and with partial cross sections of 27 and $3 \mu\text{b}$, respectively. In the same reaction, the ^{12}C ($I^\pi = 2^-, T = 1$) level at 16.6 MeV with $\Gamma = 300 \text{ keV}$ is populated. It decays to the first excited state through an isovector E1 transition of 12.2 MeV with a partial cross-section of $48 \mu\text{b}$.

The ^8Be resonance at 17.6 MeV with $\Gamma = 11 \text{ keV}$ is populated in the $^7\text{Li}(p, \gamma)^8\text{Be}$ reaction [16] at 0.44 MeV proton bombarding energy. It decays to the ground state and the particle unstable first excited state ($\Gamma = 1.5 \text{ MeV}$) with 17.6 and 14.6 MeV isovector M1 transitions having partial cross-sections of 4.5 and 2.2

mb, respectively.

It should be stressed that the aforementioned main transitions of 17.2 (E1) and 17.6 MeV (M1) are well suited for a comparative study. They have essentially the same energy, they require similar target conditions, and they can be investigated with the same arrangement, at the same experimental site. Thus it may be expected that most spurious instrumental effects will be the same for both cases.

In Fig. 1 a schematic view of the detector arrangement is shown. An arrangement of six identical ΔE - E telescopes allows the simultaneous measurement of e^+e^- pairs at 15 mean correlation angles ranging from $\omega = 20^\circ$ to $\omega = 130^\circ$. Each telescope combined a rectangular plastic scintillator plate as ΔE detector with a plastic scintillator block as E -detector. IPC-pairs from different nuclear transitions could be separated by means of the pair sum-energy derived from two

telescopes in coincidence. By mounting the telescopes on a cone at polar angles with respect to the beam of 65° in the forward hemisphere, the lepton pairs could be detected in target transmission geometry. This arrangement ensured equal path length in the target for both detected leptons. The set-up was supplemented by two larger telescopes each covering about twice the solid angle of the original telescopes mounted at polar angles of $\theta \approx 42^\circ$ and $\theta \approx 65^\circ$ respectively. These provided 13 additional data points by combining each of the large detectors with the six small ones, and one combination of the two large detectors. In this way redundancies in the e^+e^- yield for different detector combinations and in some cases different solid angles provided internal consistency checks.

The proton beam with an energy spread of less than 2% was focussed on the target with a spot size smaller than $2 \times 2 \text{ mm}^2$. Beam intensities were kept around $10 \mu\text{A}$. Target conditions were monitored by means of proton backscattering techniques [17]. For the ^{12}C studies metallic ^{11}B targets were used with thicknesses varying from $100 \mu\text{g}/\text{cm}^2$ to $600 \mu\text{g}/\text{cm}^2$, so that the amount of external pairs produced in the target could be estimated by extrapolation. For the ^8Be studies the small ^7Li resonance width required the use of thin targets. About $100 \mu\text{g}/\text{cm}^2$ Li_2O was evaporated onto carbon foils of $40 \mu\text{g}/\text{cm}^2$. The targets were replaced after typically 6 hours exposure to the beam.

The telescopes were tested and calibrated with the mono-energetic electron beam from the Giessen LINAC at energies between 6 and 16 MeV [17]. The line shapes derived from these data exhibit on the average a FWHM resolution of about 10% at 8 MeV, increasing slightly with energy to values of 16% at 14 MeV.

As an example, in Fig. 2a the calibrated sum-energy ($E_1 + E_2$) spectrum for the combination of E -detectors of telescopes 1 and 2 is shown for the reaction $^{11}\text{B}(p, e^+e^-)^{12}\text{C}$. In Fig. 2b a GEANT [18] Monte Carlo (MC) simulation for the same spectrum folded with the experimental resolution is given for comparison. The two peaks at 11 and 16 MeV represent the transitions to the first excited and to the ground state of ^{12}C . The peak below 5 MeV represents IPC of the 6.05 MeV $E0$ transition in the $^{19}\text{F}(p, \alpha e^+e^-)^{16}\text{O}$ reaction due to fluorine contamination of the boron target. This peak could be used as an internal consistency check. It follows the expected [19] $(1 + \eta \cos \theta)$ de-

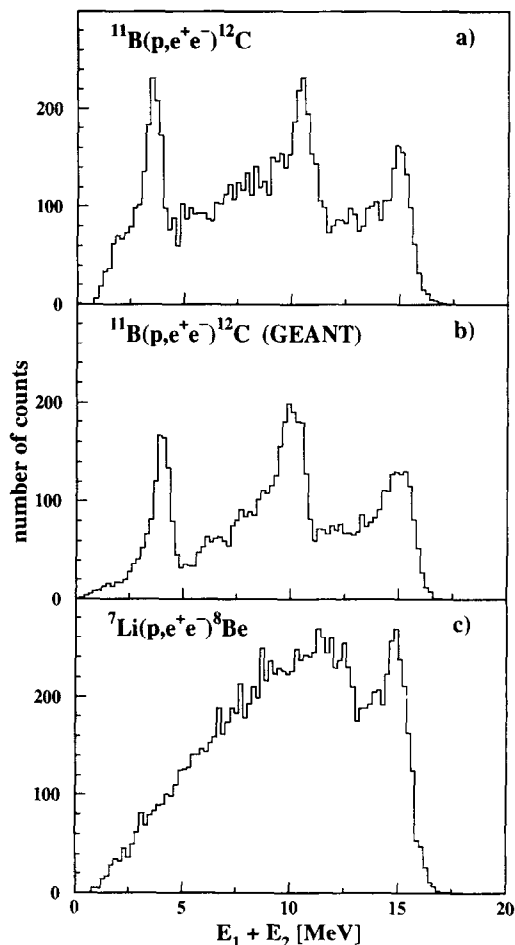


Fig. 2. Sum-energy spectra for telescopes 1 and 2 (from the E -detectors only) for a) the $^{11}\text{B}(p, e^+e^-)^{12}\text{C}$ reaction, b) the corresponding MC simulation and c) for the $^7\text{Li}(p, e^+e^-)^8\text{Be}$ reaction.

pendence for an $E0$ transition with $\eta = 1.09 \pm 0.10$. [17] In Fig. 2c the calibrated sum-energy spectrum for the same detector combination is displayed for the $^7\text{Li}(p, e^+e^-)^8\text{Be}$ reaction. The two peaks are due to the two transitions depopulating the 17.6 MeV level to the broad first excited and the ground state of ^8Be . No traces of the ^{16}O $E0$ peak are visible in this spectrum.

Detector efficiencies were determined using three independent methods: a) simply geometrically, b) by means of MC simulations, and c) by combinatorial analysis of singles events [17]. All three results are consistent within their statistical significance. For the data in this paper the geometrical efficiencies are used. In the present experiment no absolute efficiencies were

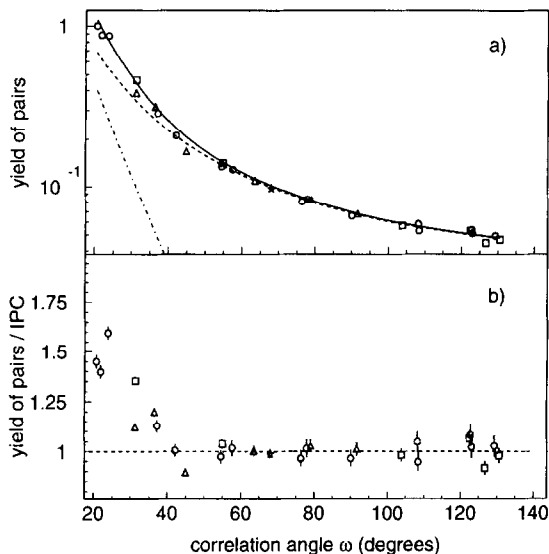


Fig. 3. (a) Measured angular correlation for the yield of e^+e^- pairs from the reaction $^{11}\text{B}(p, e^+e^-)^{12}\text{C}$, using geometrical detector efficiencies and normalised to the theoretical E1-IPC correlations [9] (dashed line) in the angular range over this range. The solid line includes effects from EPC [13] and multiple scattering calculated in a MC simulation (dot-dashed line). (b) Ratio of the experimental data and the IPC prediction (dashed curve in Fig. 3a). Open circles denote correlations between the six small detectors, open triangles between one large detector (7) and small detectors, open squares between the other large detector (8) and small detectors. The data point at 68° represents the correlation between the two large detectors (7) and (8) (see also Fig. 1).

determined with adequate precision. To account for differences in the low-energy thresholds of the detectors, in particular for the large detectors, normalisation factors of 0.78 and 0.95 were applied to all combinations of the small telescopes with telescope 7 and 8 respectively. The detector combination 7-8 consequently has been normalised by the product of both factors. The level of systematic uncertainties due to detector, beam and target alignment, as well as due to energy and angular smearing, have been estimated. The overall effect is expected to be roughly of the same size as the statistical errors. This is confirmed by the spread – beyond statistical fluctuations – in data points of Figs. 3 and 4 where approximately the same central ω values are obtained from different pairs of detector telescopes.

In Figs. 3a and 4a the measured angular correlations of e^+e^- pairs with a sum energy above 5 MeV are shown for the reactions $^{11}\text{B}(p, e^+e^-)^{12}\text{C}$ (E1-

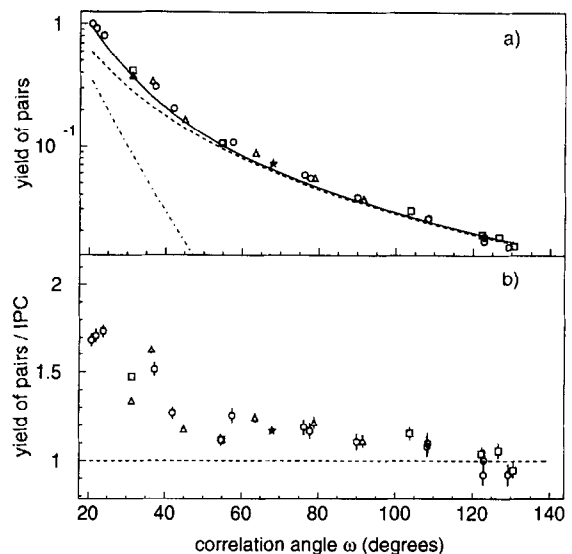


Fig. 4. (a) Measured angular correlation for the yield of e^+e^- pairs from the reaction $^7\text{Li}(p, e^+e^-)^8\text{Be}$ and curves similar to Fig. 3a. (b) Ratio of data and IPC obtained in the same way as in Fig. 3b.

transitions) and $^7\text{Li}(p, e^+e^-)^8\text{Be}$ (M1-transitions), respectively. The data sets are scaled to unity at the smallest correlation angle measured. The dashed lines represent IPC distributions for non-aligned nuclei [9] normalised to the data points at large ω ($\omega > 120^\circ$), where relative contributions from EPC and multiple scattering are minimal. The latter clearly show up at $\omega < 50^\circ$ and mainly arise from the carbon-fibre tube used as vacuum window for the leptons.

The shape of these contributions for the particular geometry of our apparatus (dot-dashed lines in Figs. 3a and 4a) has been determined by means of GEANT Monte Carlo simulations [17]. At 21° the number of pairs due to EPC and multiple scattering was calculated for both reactions to be typically 45% with respect to IPC. However a value of 57% is needed to achieve good agreement for the ^{12}C data. Considering the uncertainties in the nontrivial determination of the EPC contributions this appears acceptable to us. Moreover, the difference does not influence the data at $\omega > 50^\circ$ to a significant extent. The solid lines in Figs. 3a and 4a represent the sum of IPC (normalised to the data at $\omega > 120^\circ$) and EPC, both including multiple scattering. As the angular correlations of e^+e^- pairs due to IPC decline by almost two orders of magnitude in the ω range considered, any possible devia-

tion from IPC would show up more clearly in a presentation of the ratio of the data and the IPC predictions, as shown in Figs. 3b and 4b.

Concerning possible effects from nuclear alignment the following can be said. For ^{11}B -proton capture to the 17.2 MeV level in ^{12}C followed by the ground state transition, a small alignment arises only in the a_2 -coefficient ($a_1 = 0$, $a_2 = 0.15$) of the γ -angular distribution [14]. The same holds for the 12.8 MeV decay of this level, although here a rather strong a_1 component ($a_1 = 0.5$, $a_2 = 0.14$) has been deduced [14]. The latter transition, however, only contributes at the 10% level. The 12.2 MeV transition has been reported [14] to be isotropic. Similarly, the ^7Li -proton capture to the 17.6 MeV state in ^8Be at 440 keV has been found [20,21] to be isotropic to within 6% ($a_1 = 0.056$ and $a_2 = 0.008$) for both the 17.6 and 14.6 MeV transitions. Furthermore the experimental set-up was designed such as to be almost insensitive to alignment. Calculations using alignment [10] showed that any remaining effects (for ^{12}C only) are small compared to the statistical accuracy. Consequently, nuclear alignment has been neglected in this paper.

For the ^{12}C data on the 17.2 and 12.2 MeV E1 transitions relative to IPC (matched at $\omega > 120^\circ$, see Fig. 3b), a fit with a smaller error can be obtained over an extended range down to 50° . No deviation beyond the 2σ level is observed over this range. This allows us to deduce upper limits for the branching ratios of scalar and vector bosons ranging from 3.7×10^{-5} to 1.1×10^{-5} corresponding to 6 and 15 MeV/ c^2 invariant mass respectively, two orders of magnitude below the value 3.9×10^{-3} [9] of the IPC coefficient. In combination with existing bounds these limits constrain scalar bosons in the allowed mass-lifetime window accordingly. A more detailed discussion on the experiment and the analysis will be given in a separate paper [22].

For the ^8Be data on the 17.6 and 14.6 MeV M1 transitions, when treated in the same way as the ^{12}C data, a deviation at the 4.5σ level appears in Fig. 4a and more clearly in Fig. 4b, for ω between 50° and 110° . To our knowledge nuclear structure effects can not account for the observed deviation from standard IPC. In particular E1-M1 IPC mixing – due to non-resonant s -waves [23] at the few permille level [24] in addition to the resonant p -waves in ^7Li proton capture at 441 KeV – does not seem to provide an explanation.

Recent QED calculations by Soff et al. [25] show that standard IPC [9,10] theory grossly underestimates M1-IPC in the few hundred keV region at large ω for aligned heavy nuclei. Although such an effect cannot explain the deviation, it indicates that IPC may not be as well predicted at large angles as usually understood.

We notice that MC simulations for a short-lived boson with mass of about 9 MeV/ c^2 , competing in both the 17.6 and 14.6 MeV transitions, can approximately reproduce the broad deviation with respect to IPC. A pursuit of the original motivation to narrow the allowed mass-lifetime window for pseudoscalar and vector bosons now seems to be impeded. The upper limit for the branching ratio would be 1.5×10^{-4} , a factor five larger than the value 3.1×10^{-5} obtained for a 9 MeV/ c^2 scalar or vector boson in the ^{12}C case. However, the bound is still small compared to the theoretical IPC coefficient [9] 3.2×10^{-3} . The relatively high sensitivity of the present experiment might explain why the deviation has previously not been observed [26,27]. Further experiments are needed to verify the here reported unusual behaviour in M1 IPC.

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